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Estimation of ionospheric parameters by propagation of electromagnetic waves at low latitude

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Abstract : In this paper, some results related with the propagation characteristics of electromagnetic waves in very high frequency (VHF), very low frequency (VLF) and extremely low frequency (ELF) ranges through the ionospheric plasma have been reported. Amplitude of scattered VHF signal is recorded and morphological features of ionospheric plasma irregularities are studied. Auto-correlation and power spectrum analysis are carried out to estimate scale length which varies between 200 m to 500 m and drift velocity of plasma irregularities which varies between 75 m/sec to 200 m/sec. VLF waves propogate in guided and ducted mode. The VLF whistler wave spectrum is analysed to estimate electron density of ionospheric plasma and the total electron content in a flux tube of unit cross section. Dispersion analysis of ELF proton whistlers is carried out to estimate ionospheric proton density and proton temperature. The results are found in good agreement with the other reported works.

Keywords . Ionospheric irregularities, proton whistler, scintillation.

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1. Introduction

Ionosphere is a fascinating part of the upper atmosphere, which apart from its academic interest has an applied value in radio communication. The fluctuations in the electron density known as irregularities cause the ionosphere to behave like inhomogenous medium and produce change in amplitude, phase and frequency of the electromagnetic waves propagating through them. By analysing the wave parameters, information about the medium through which it has propagated can be derived. The ionospheric irregularities may be enhanced or depleted of electron density relative to ambient. These irregularities lie, for the most part, in the *F*-layer of the ionosphere [1]. Herman [2] reviewed the experimental evidence and calculated that the irregularities are field aligned, typically having a size of about 1 km transverse to the magnetic field, and are elongated along the field. The generation and movement of these irregularities are studied using multi-frequency signals and recording them at multistations [3–5].

In the present study, we have considered propagation of electromagnetic waves through the irregular ionosphere in three frequency ranges namely : very high frequency (VHF), very low frequency (VLF) and extremely low frequency (ELF) range. For VHF wave propagation, we have considered 244 MHz signal radiated from geostationary satellite FLEETSAT parked at 73°E. The source of VLF and ELF waves is taken as lightning discharge present in the atmosphere.

The VHF signal from satellite usually traverses the plasmasphere, ionosphere and lower atmosphere, before, being received on the Earth surface. In the plasmasphere, plasma density is much smaller as compared to ionosphere

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and hence the fluctuations in the amplitude, frequency and phase of the wave are varied much more while propagating through the ionosphere as compared to plasmasphere or lower atmosphere. These fluctuations are collectively known as scintillations [6]. Thus, study of scintillations became an important tool for studying the irregularities of electron density in the ionosphere. Morphological studies have shown that scintillation is most severe and prevalent in the north of auroral zone and near the geomagnetic equator [7].

It is well established that the return strokes of lightning discharge radiate copious amount of energy spread over wideband of electromagnetic spectrum. Part of this energy penetrates the lower ionosphere and traverses the outer ionosphere propagating along geomagnetic field lines in whistler mode from one hemisphere to the other hemisphere. These VLF/ELF whistlers carry with them, the signature of the structural details of the plasma medium through which they travel and on analysis, unravel significant information regarding the electron density distribution, the distribution of electric field, upward/downward transport of ionization and various types of wave instabilities taking place in the medium through which they pass [8].

The ELF proton whistlers are a dispersed form of lightning impulses observed in the upper ionosphere which appear on frequency-time spectrograms as rising tones asymptotically approaching the proton gyrofrequency [9,10]. The frequency spectrum of proton whistler is explained by considering the propagation of ELF electromagnetic waves through a model ionosphere having several types of ions [11].

In the present paper, we report the information derived about the ionospheric irregularities from the observations of VHF amplitude scintillations recorded at Varanasi, ELF proton whistlers recorded by Injun-3 Satellite and VLF whistlers recorded at Varanasi. The diurnal, seasonal and annual variation of irregularities are studied. The electron density and the proton density are estimated.

2. Results and discussion

(a) Characteristics of ionospheric irregularities :

The amplitude scintillations of 244 MHz signals from geostationary satellite FLEETSAT situated at 73°E longitude are continuously monitored at Varanasi (geomag, latitude 14°55'N) from January 1991 to December 1999 using a VHF receiver AKASH, 11-element Yagi-Uda antenna and a strip chart recorder [12]. In addition to the normal chart, recording data were also recorded digitally at a sampling rate of 10 Hz on a few nights. The nighttime data are analysed to study the nocturnal variation of scintillation occurrence in different months and seasons.

The distribution of patch duration in the winter, summer and equinox seasons of the years 1991 to 1999 is shown in Figure 1. This shows that over Varanasi, ionospheric irregularities occur in small patches and patch duration is

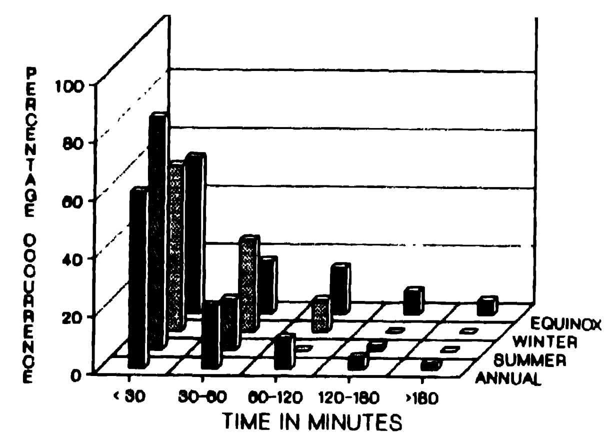


Figure 1. Distribution of patch duration in different seasons of 1991–1999

usually <30 minutes. Similar patchy occurrence of irregularities was also reported by Mathew *et al* [13] for Rajkot. The nighttime intensity scintillation statistics beginning from 1991 to 1999 is shown in Figure 2. The different hatching show fade depth indices in dB ranging

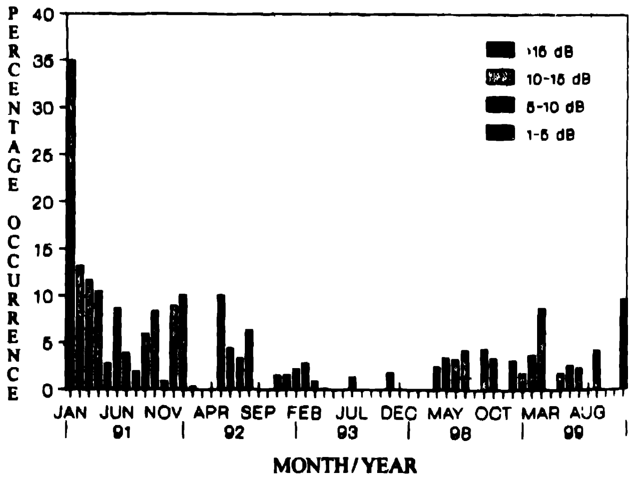


Figure 2. The nighttime intensity scintillation statistics from 1991 to 1999.

from ≥1 dB to 20 dB. The figure clearly shows that in summer months, the fade depth is mostly less than 5 dB but in winter and equinox months, it is between 5 to 15 dB. The effect of solar activity shows that the amplitude of irregularity decreases with decrease in solar activity. While the effect of magnetic activity shows that there is a reduction in the occurrence of irregularities on magnetic disturbed days [14].

More meaningful information about the irregularities can be derived from digital scintillation data. Various samples of the scintillation records have been analysed for estimating power spectra. One typical example of the power spectra computed from the data recorded on 22nd January, 1992 is shown in Figure 3. The spectral slopes between 0.1–1 Hz have been computed for various samples which show that

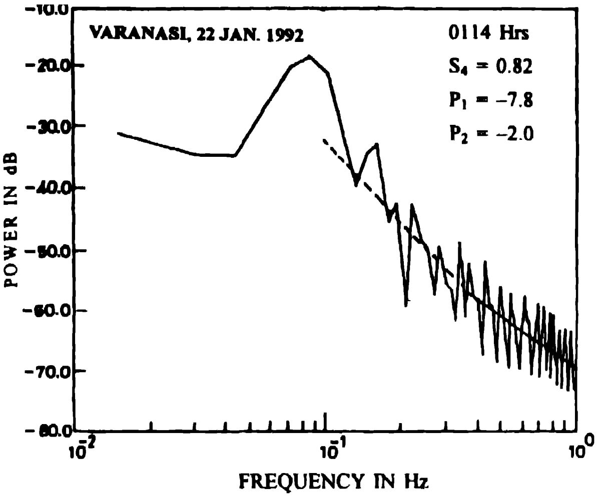


Figure 3. A typical example of power spectra of amplitude scintillation.

the spectral index varies between 2 and 8 with mean value of 4. .This value is in close agreement with the *in-situ* observations from SHAR [15].

Using weak scattering theory of phase changing screen model, the velocity of irregularity is given as [16].

$$V = (\lambda z)^{1/2} f_{\min}, \tag{1}$$

where z is the height of the phase screen, λ is the signal wave length and $f_{\min}$ is first Fresnel minimum in given spectra. Considering z = 350 km, the velocity of irregularities for various samples are computed and it is found to lie between 75 m/sec to 200 m/sec. The size of the irregularities are determined from its definition according to which the size of the irregularity is equal to the distance at which the autocorrelation function falls to 0.5 [17]. Large number of samples are analysed and characteristic lengths are computed which varies between 200 m to 500 m.

(b) Determination of electron density and total electron content :

At low latitude station Varanasi (geom, lat 14°55'N), whistlers of natural origin are being recorded on routine basis using a simple *T*-type antenna, Pre/main amplifier and cassette recorder. The recorded whistlers are analysed by Advanced VLF Data Analysis System (AVDAS). This system is completely dedicated to whistler analysis. At Varanasi, whistlers are observed usually in nighttime. The predominant occurrence is in the post-midnight periods. The whistlers at Varanasi are observed in large number only during geomagnetic storm periods. The marked enhancement in whistler activity has been interpreted in terms of ionization duct formation during magnetic storm periods [8]. For the present study, we have chosen whistlers recorded on 9th March 1991 between 0025 h and 0330 h IST. During this period, *Kp* index varied between 3 and 4 and large numbers of whistlers were recorded. Figure 4 shows sample of the whistlers recorded on 9th March 1991.

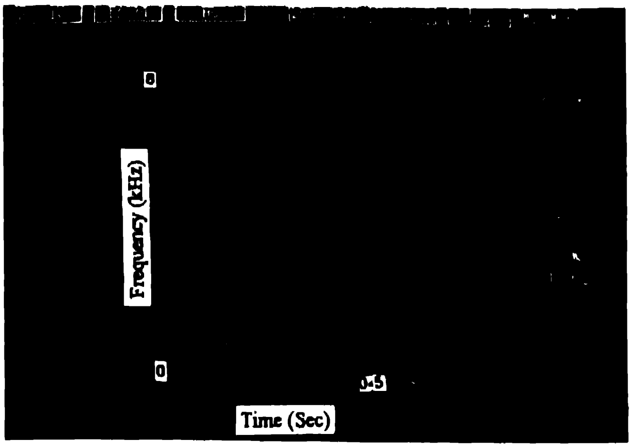


Figure 4. A sample of whistlers recorded on 9th March 1991 at Varanasi

In the whistler analysis, frequency and corresponding arrival time are measured from the recorded spectrogram and dispersion is evaluated. The group travel time for the whistler wave from the source to the observer is written as

$$t = t_s + t_w + t_{\text{ion}} + t_{\text{mag}}, \tag{2}$$

where t_s is the time taken by the sferics propagating through the Earth-ionosphere waveguide from lightning source to the receiver, which is negligible small, t_w is the time taken by the whistler wave in the Earth-ionosphere waveguide after exiting from the duct, t_{ion} is the time delay due to ionospheric path, t_{mag} is the time delay for magnetospheric path. Singh *et al* [18] have suggested an average value of $t_w \sim 10$ ms. The time delay due to ionospheric path can be written as [19].

$$t_{\text{ion}} = \frac{1.4(f_0F_2)}{f^{1/3}}\sec. \tag{3}$$

where (f_0F_2) is the critical frequency of the F_2-layer of the ionosphere in MHz and f is the wave frequency in Hz. Based on the measurement of (f_0F_2) at nearby station, we consider its representative value for the present computation as 5 MHz. Thus from eq. (3), the t_{ion} for 5 KHz whistler wave frequency comes out to be 98 ms. Thus, with these corrections, we can write [18,20]

$$t - t_w - t_{ion} = t_{mag} \quad \frac{\mathrm{Re}\, L}{2C}\int^{\phi'} \frac{f_p(\phi)}{f^{1/2}}$$

$$\frac{f_{He}\cos^6\phi_0(1+\sin^2\phi)}{\cos\phi\left[f_{He}\dfrac{\cos^6\phi_0}{\cos^6\phi}(1+3\sin^2\phi)^{1/2}-f\right]} \tag{4}$$

where f_0 and f_{He} are local electron plasma frequency and equatorial electron gyrofrequency respectively. ϕ' is the geomagnetic latitude at reference height 1000 km, R_e is the Earth's radius, L is the McIlwain parameter and ϕ_0 is the geomagnetic latitude of the field line at the surface of the earth. At low latitudes, $f_{He} >> f$ and considering electron density distribution along dipolar geomagnetic field line to be $N = K^2 R^{-3}$ [21], (where K is a constant), eq. (4) in terms of dispersion is written as

$$D_0 = D_{obs} - D_i \quad \frac{9LR_0^{-1/2}K}{2cf_{He}^{1/2}}$$

$$\int^{\phi'} \cos\phi(1+3\sin^2\phi)^{1/4}d\phi, \tag{5}$$

where D_{obs} is the measured dispersion with correction which was obtained from the slope of t *versus* $f^{-1/2}$ plot and $D_{ion} = t_{ion} f^{1/2} = 7.0$. Thus, K is determined by integrating eq. (5) and using the measured dispersion of the recorded whistlers. Once K is known, the electron density distribution along a geomagnetic field line is determined. The path of propagation (L-value) of whistlers is evaluated using the relation $L = 9.56\, f_{Heq}^{-1/3}$ which yields the path of propagation lying between L = 2.12 to 2.76 although the L-value of Varanasi is 1.07. Thus, it is seen that whistlers are propagated along higher L-values in the magnetosphere and after exit from the ionosphere, propagated through Earth-ionosphere waveguide towards the equator which are received at ground station corresponding to lower L-value.

The equatorial electron density is estimated by analysing all the recorded whistlers. The variation of equatorial electron density as a function of L-value is shown in Figure 5.

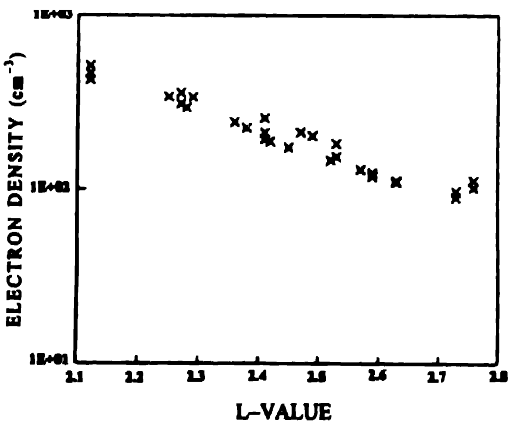


Figure 5. Variation of equatorial electron density as a function of L-value.

The minimum and maximum values of the equatorial electron density come out to be 1.0×10^2 and 5.0×10^2 electrons cm^{-3} respectively at $L = 2$ whereas Tarcsai *et. al.* [22] has reported 2.0×10^4 electrons cm^{-3} at L = 1.4 and 5.0×10^2 electrons cm^{-3} at L = 3.2. Thus, our results are in good agreement with previously reported values by other workers.

The total electron contents in a magnetic flux tube of unit cross sectional area at the reference height is estimated by evaluating the integral [18]

$$N_T = \int_{ref}^{Equator} N(S)\frac{B_r}{B(S)}dS, \tag{6}$$

where B_r is the magnetic field at the reference level, $B(S)$ is the magnetic field strength at any other point 'S' along the geomagnetic field line and dS is elementary path length along the whistler path. The total electron content shows slight decrease with L-value as plotted in Figure 6 although

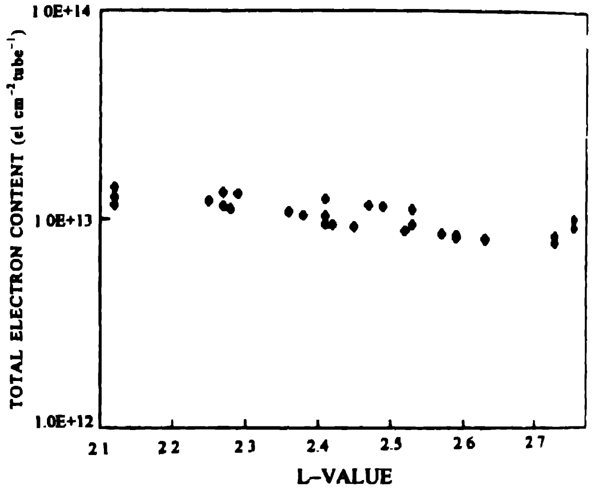
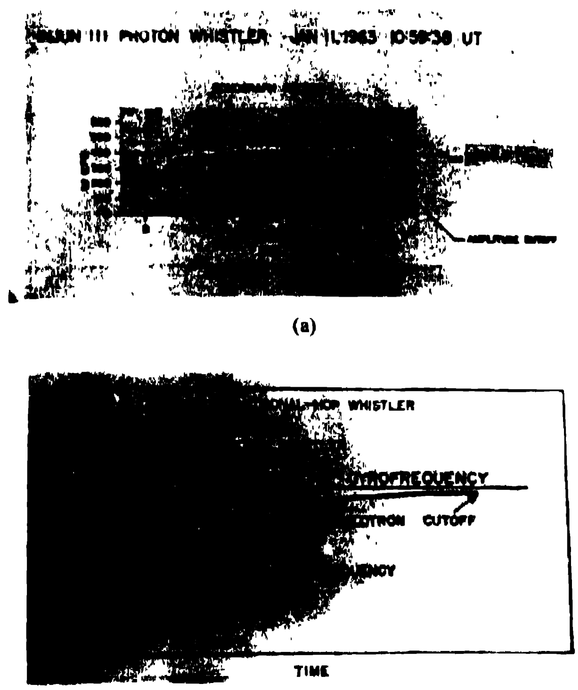


Figure 6. Variation of total electron content in a flux tube with L-value.

all the values lie between 8.4×10^{12} and 1.5×10^{13} electrons/cm^2-tube. These values of total electron content are of the same order as reported by other workers [22–24].

(c) Determination of proton density and proton temperature:

The propagation of ELF electromagnetic waves through a model ionosphere containing several types of ions have been studied by several workers [9–11,25]. The dynamic spectrogram of proton whistlers is shown in Figure 7. It is observed that the amplitude of proton whistlers decreases suddenly at a frequency slightly below the local proton gyrofrequency. The abrupt amplitude cut-off may be due to collisional damping, cyclotron damping or accessibility conditions. The proton whistlers are recorded by satellites and are observed along with a short fractional hop electron whistlers more frequently during local nighttime than during local daytime. They have never been observed to occur below 442 km during local nighttime or below 640 km during local day time [26]. The occurrence rate is 3 times more in nothern hemisphere as compared to in southern hemisphere.



(a)

(b)

Figure 7. (a) A typical example of proton whistlers recorded by satellite [9] and (b) Frequency time spectrogram of the proton whistler

We consider the proton whistler propagating through an ionospheric plasma consisting of a neutral mixture of three types of singly charged positive ions (H^+, He^+, O^+) and electrons, embedded by a static magnetic field For proton whistlers, $\omega^2 < \omega_{He}\,\omega_{Hi}$ where ω is the wave frequency, ω_{Hi} is the proton gyrofrequency and ω_{He} is electron gyrofrequency. The time taken by the proton whistler from the source to the satellite (group travel time) is given by [10]

$$= \sum_i \frac{\omega_{pi}\,\omega_{Hi}^{1/2}}{C\omega'_{Hi}\,\Delta\omega_i^{1/2}} + \sum_i \frac{2}{7}\,\frac{V_{thi}^2\,\omega_{pi}^3\,\omega_{Hi}^{3/2}}{C^3\omega'_{Hi}\,\Delta\omega_i^{7/2}}, \quad (7)$$

where ω_{Hi} is the gradient of proton gyrofrequency along the raypath $\Delta\omega_i = \omega_{Hi} - \omega$, V_{thi} is termal valocity of proton and ω_{pi} is the proton plasma frequency. In the above, the first term is the dominant term and the second term arises due to thermal effect and is proportional to the proton temperature and gradient of proton gyrofrequency. The expression for the proton density deduced from the eq. (7) is written as [10]

$$n(H^+) = \frac{m_i\varepsilon_0 C^2}{e^2}\left[\frac{\partial\omega_{Hi}}{\partial s}\right]^2 \frac{S^2}{\omega_{Hi}}$$

$$\times\left[1 - \frac{4}{7}V_{thi}^2\left(\frac{\partial\omega_{Hi}}{\partial s}\right)^2 \frac{S^2}{\Delta\omega^3}\right], \quad (8)$$

where $S = \frac{\Delta t}{\Delta p}$, $P = (\omega_{Hi} - \omega)^{-1/2}$ and S is evaluated from the measurement of dispersion of proton whistlers. If the location of the observation point is known, the ω_{Hi} and $\frac{\partial\omega_{Hi}}{\partial s}$ can be estimated. Substituting these parameters in eq. (8), proton density can be evaluated. We have computed the proton density of the upper ionosphere using eq. (8) and the results are tabulated in Table 1. The required parameters for the computation are taken from the proton whistlers recorded on board injun 3 satellite [26].

Table 1. Proton density and proton temperature determ[illegible] from proton whistlers

Occurrence date and time (universal)	Altitude (km)	Invariant latitude (degree)	Proton density $n(H^+)(\times 10^9 m^{-3})$	Proton temperature (K)
January 7, 1963, 10 08 19	1595	40 2	6 92	1050
January 11, 1963, 09 08 26	968	55 8	1 61	750
January 11, 1963,	1308	42 [illegible]	11.33	600

We have estimated proton temperature by studying the damping of proton whistlers. Total attenuation due to spatial cyclotron damping is given by [10]

$$\beta = 4.3A\,t^2 \exp(-B\,t^{-6})\,dB, \quad (9)$$

where $A = (\sqrt{\pi}/3)V_{thi}\,\omega'_{Hi}$

and $B = (\omega_{pi}^4\,\omega_{Hi}^2)/(c^4\,V_{thi}^2\,\omega_{Hi}^6)$.

We have plotted the cyclotron damping with temperature for fixed group travel time 4.5 sec, which is shown in Figure 8. It is clearly seen that the damping increases with

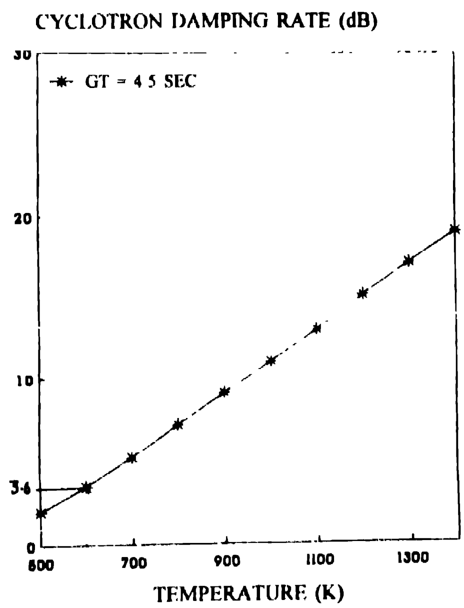


Figure 8. Variation of cyclotron damping with proton temperature for group travel time 4 5 sec

temperature. We can easily evaluate the proton temperature by comparing the experimentally measured cyclotron damping as a function of group travel time with the theoretically evaluated damping for various temperatures. The results of estimated proton temperatures are given in Table 1. These computed ionospheric proton densities and proton temperatures are in good agreement with that of other workers [10,11,27].

3. Conclusions

(a) The scattering of VHF waves by ionospheric irregularities shows that irregularities over Varanasi occur in small patches and patch duration is usually less than 30 min. The increase of solar activity normally increases the amplitude of irregularities. The drift velocity of these irregularities is found to vary from 75 m/sec to 200 m/sec and the characteristic length varies from 200 to 500 m.

(b) The VLF whistlers recorded at Varanasi yields the upper ionospheric electron density in the equatorial region which varies between 100 and 500 electron cm^{-3} as L varies from 2.76 to 2.12. The total electron content in the flux tube of unit cross section lie in the range 8.4×10^{12} and 1.5×10^{13} electrons/cm^2-tube.

(c) The propagation of ELF proton whistlers through the ionosphere gives the ionospheric proton density of the order of 10^9 m^{-3} and the study of cyclotron damping gives the proton temperature.

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